Relaying Short Lines

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Lines may be classified as short when the distance between the ends of the line is relatively small, or if the impedance of the line is low. In terms of line length, short lines are typically those lines less than 10 miles long. Many problems associated with the so called short lines, however, are actually related to the ratio of the source impedance to the line impedance. As the ratio increases, the application complexities increase. In this regard, a 10 mile line with a low source to line impedance ratio may be considered as a "longer" line while a 100 mile line with a large source to line impedance ratio may exhibit many of the problems associated with "short" lines. In the past, many short lines were protected by current only schemes such as phase comparison or current differential. Today, distance relays are being used more than ever before. This paper will present a brief overview of some advantages and disadvantages of both current only schemes and distance\directional schemes, as well as some of the problems that may arise as the source to line impedance ratio increases.

Current Only Schemes

Phase comparison relays may use individual phase currents, or a composite signal that is derived from the sequence components of the phase currents may be used. The phase angles of the individual currents or of the composite signals are compared via a communication channel. The current magnitude is used only on a local basis. A through fault or load condition is indicated when the current signals are out of phase. An internal fault is indicated when the current signals are in, or very nearly in phase.

Current differential schemes may also use a composite signal or they may use individual phase currents. In a current differential scheme, both the magnitude and angle of the currents are exchanged among the terminals.The current differential schemes typically compare the magnitude of an operate signal and a restraint signal.The operate signal is proportional to the vector sum of the local and remote current signals, while the restraint signal is a percentage of the algebraic sum of the magnitudes of the local and remote current signals.

Current only schemes such as phase comparison and current differential do not require potential transformers. This somewhat reduces the complexity of the relay, but at the same time reduces the capability of the relay. Current only schemes are very dependent on the performance of the associated communications channel. A failure of the communications channel may result in a failure to trip or a false trip. On short line applications, the channel for the current only scheme can be a fiber optic channel or dedicated pilot wire.

A current only scheme is limited to overcurrent units for direct tripping and for backup protection. The usefulness of a direct trip overcurrent unit on a short line is a function of the source impedance as well as the line impedance. Consider the transmission line of Figure 1. Table 1 shows the 3 phase fault currents for faults at both ends of the line as the source impedance is increased.

TABLE I

Zs	ZS/ZL	IF1	IF2	Iset (1.25xIF2)
0.275	1.0	244	122	152
0.550	2.0	122	81	102
0.825	3.0	81	61	76
1.105	4.0	61	49	61

It can be seen from Table I that as the ratio of source impedance to line impedance increases, a direct tripping overcurrent unit becomes less effective. When the ZS/ZL ratio is larger than 4, the direct trip can not be set with the typical 125 percent margin.

Fault resistance and arc resistance typically will have little effect on the performance of a current only scheme because the fault detecting elements may be set very sensitively. These sensitive settings, however mean that the scheme will be responding to many external faults. Every external fault represents an opportunit for the scheme to in other words, if the protective relays do not see an external fault they can not misoperate for it. In the case of a current only scheme, channel problems may cause the scheme to trip undesirably.

Distance/Directional Schemes

Relay schemes that use potential are generally more complex than current only schemes. The ma'or advanta e of using potential in the rela scheme is the reduction in the number of external faul ts for which the relay will respond. Thus th e probability of false tripping for an external fault as a result of erroneous outputs from the associated channel is greatly reduced. This is especially true of distance schemes.

The directional schemes have an advantage over the current only schemes in terms of security in that they can be designed to detect external faults immediately and set up transient blocking. The directional schemes can employ combinations of zero and positive sequence currents that result in a reduced response to external faults when compared to current only schemes using phase currents or negative sequence currents.

Current Sensitivity

In general as the reach setting of a distance relay is reduced, the fault current re uired to operate the relay increases and operating time of the relay also increases. Thus for short ines, more fault current is required for the relay to operate. Consider the relay shown in Table II. The current listed is the current required for no more than ten percent pullback; that is, the relay will reach at least ninety percent of its set reach if the fault current is equal to or reater than that shown in the Table. Note that as the base reach tap of the relay is reduced (shorter reach), the current required increases inversely.

TABLE II

Base Tap)	Minimum Current for 10% Pullback
0.4	1.0
0.2	2.0
0.1	4.0

For many short line applications the sources are very strong and the fault currents high; however, for those systems with high source to line impedance ratios, the current sensitivity of the relay must be considered.

Arc/Fault Resistance

The actual value of arc resistance in a fault is difficult to evaluate. It is known, however, that the resistance of an arc increases with the length of the arc and has an inverse relationship to the current in the arc. Reference 1 presents an approximation of the arc voltage for primary fault currents in excess of 1000 amperes:

$$Varc = 25 \times KV \text{ (volts per phase)}$$

where, KV is the rated voltage of the line in kilovolts.

This approximation can be used to provide a rough estimate of the expected response of a distance relay to the arc resistance in a fault. The radial line of Figure 1, assuming a 500KV system with a PT ratio of 4343:1, was used to calculate the voltage at the relay location and the drop in the line for various source to line impedance ratios. Based on the approximations above, the arc drop voltage is equal to 2.88 Vrms secondary. As the source to line ratio increases, the voltage drop in the arc becomes a significant percentag of the voltage at the relay location. With a source to line im edance ratio of 100, the arc voltage is greater than four times the voltage drop in the line.The apparent arc impedance seen by the relay is thus greater than 4 times the line impedance.

Note that infeed from another source will not affect the magnitude of the apparent arc impedance seen by the relay, but will affect the angle of the im edance. The change in angle could cause a distance function to overreach, or underreach, or have no effect at all, depending on the design of the function. Because the magnitude of the apparent arc impedance is the greatest at high source to line impedance ratios, the performance of both phase distance and ground distance functions will be similarly affected under those conditions. At low source to line im edance ratios, the apparent arc impedance is very low and neither type of distance function will be affected to any great extent.

TABLE III

ZS/ZL	Varc	Vrelay	Vline	Varc/Vline
0.25	2.88	53.63	53.60	0.054
01.00	2.88	33.59	33.50	0.086
10.0	2.88	6.73	6.01	0:480
30.0	2.88	3.60	2.16	1.330
100	2.88	2.95	0.66	4.360

In faults involvin ground, the total resistance in the fault is made up of the arc resistance plus a fault resistance that can be very large depending on the components involved in the fault. For example, a tree fault, or a fault to ground through a fire can have a very large resistive component relative to the arc resistance. The effect of infeed on this component is to magnify the resistance as well as to shift it in phase angle. Primarily because of the magnification, ground distance functions may not be very effective for these conditions since ground distance relays become less effective as fault resistance increases. Where high resistance f aults are a significant application consideration, then the choice is between current only schemes and directional overcurrent schemes.

Potential Source Accuracy

As the source to line impedance ratio increases the voltage at the relay potential location decreases. Korejwo et al (Ref. 2) point out that the lower accuracy of the otential source at these lower voltages may limit the application of a Zone 1 direct trip unit on short lines.

CVT Transients

Since the advent of high speed solid state protective relays, the transients associated with the capacitive coupling devices used to obtain the line voltages for the relay systems have been known to cause problems in the performance of distance relays. Except for aberrations too small to be of any significance, wound type potential transformers accurately reproduce power system voltages, even under transient conditions.Coupling capacitor potential devices, on the other hand, can introduce significant transient errors. Aside from the design of the CVT itself, the extent and duration of these errors depend upon several factors, namely:

a) Make up and magnitude of the burden connected to the secondary of the coupling device
b Fault initiation angle
c) Ratio of the voltage prior to the fault to the voltage during the fault (Source to line impedance ratio)

In general, there are two areas where the transient behavior of the CVT can significantly affect relay performance. First is the loss of directionality for faults in the reverse or non-trip direction; second is the transient under-reach or over-reach of a zone 1 element for a fault beyond the end of the protected line.

1. Directional Action

The directional action of a mho relay is extremely important to the performance of any directional comparison or step distance relaymg scheme, In general, all relays include memory action so that they "remember' the voltage that existed prior to the fault for a short time after the fault occurrence. This memory action is important to the performance of a mho distance relay regardless of the transient response of the potential source. It provides a substantial magnitude of prefault polarizing voltage to the relay after a close-in fault occurs so that a reliable reference quantity is available to make a trip or no-trip decision even for zero voltage faults. Note that a truly directional mho relay can not operate on a steady state basis with zero voltage applied.

The transient error of a CVT is greatest for zero voltage faults because any output is pure error. Therefore, the most onerous situation for directional action of a mho relay would be a zero voltage external fault at the relay potential location. Figure 2 shows a simple system with a 3 phase fault on the bus behind the relay. For this condition the steady state voltage at the relay is zero. Transiently, however, the voltage seen by the relay is a function of the design of the particular CVT and the burden connected to it. A typical waveform is shown in Figure 3. Note that for this case, the polarity of the voltage from the CVT is out of phase with the prefault voltage in the second half cycle after the fault occurs. For a phase angle comparator type of mho distance relay a trip output is produced when the operating signal (IZ-V) is out of phase with the polarizing signal (Vpol). For a relay without memory action, this can result in a reversal of the polarizing quantity relative to the IZ-V operating quantity that will result in a misoperation.The use of memory action in the polarizing circuit will insure proper directional action for this case if it can ride over the CVT transient error. However, a misoperation may still occur, if the magnitude of the IZ signal is less than that of the CVT transient. This misoperation is caused by the phase reversal of the IZ-V operating signal not by the polarizing signal; therefore the use of cross-polarization or memory voltage will not prevent a misoperation. This problem is most evident when the magnitude of the IZ signal in the relay is small. This can occur when the fault current is low and/or when the reach of the relay is small.

2. Transient Underreach-Overreach

Figure 4 shows the construction of a phase angle comparator mho distance unit on the RX dia ram. Note that as the fault location approaches the end of the line, the magnitude of the IZ-V (operating signal approaches zero. As the magnitude of IZ-V is reduced, the effect of any erroneous voltage, sueh as the CVT transient, is increased. The transient over or under reach of a distance relay will therefore be affected by the transient response of the potential transducer. If the output voltage tends to be momentarily higher than what it should be then the distance relay will tend to underreach for a short period of time for faults near the reach setting. This will delay the trip output until the transient goes away, thus slowing down the operating time for internal faults near the reach setting. On the other hand, if the output voltage is momentarily lower than the true value, the relay may overreach and trip for faults beyond the steady state reach setting. In either case if the distance relay under consideration does not provide a first zone function, the transient reach characteristic is not very significant. However, for first zone functions the transient reach characteristics are important or obvious reasons.

For the simple system of Figure 5, with an external fault on the remote bus with a Zone 1 set for 90 ercent of the impedance of the protected line, the current and voltage, as well as the Vpol and IZ-V rela signals, are shown in Figure 6. Note that in the second ha1f cycle after the start of the fault the CVT transient has caused the IZ-V signal to reverse polarity with respect to the polarizin voltage. This is the operating condition for the phase angle com arator unit. This over reach is similar to the reverse fault in that the problem is most evident when the magnitude of the IZ signal in the relay is small. This can occur when the fault current is low and/or when the reach of the relay is small. This can be the situation when the relay is applied to a short line with a weak source behind the relay, but can also occur on longer lines if the source to line impedance ratio is large.

Effect of the Source to Line Impedance Ratio (ZS/ZL)

The possible over-reach of a Zone 1 distance unit due to CVT transients is generally more probable on short lines rather than on long lines. However, it is not actually the line length that aggravates the problem but rather the ratio of the source and line impedances. Table IV shows the per unit values of gevolta and IZ-V for the simple system of Figure 5 with a fault applied at 85 percent of the relay reach (relay set for 90 percent of the line).

TABLE IV

ZS/ZL	Voltage	IZ-V
0.25	0.7537	0.1330
1.00	0.4334	0.0765
10.00	0.0711	0:0125
30.00	0.0249	0.0044
100.0	0.0076	0.0013

Note that the magnitude of the IZ-V signal, which is the operating quantity for the mho distance relay, becomes very small as the source to line ratio increases. For a ZS/ZL ratio of 30, the magnitude of the voltage is less than 5 % of the nominal rated voltage; at ZS/ZL of 100, it is less than 2 %. For a ZS/ZL ratio of 10, the ma nitude of the IZ-V is less than 2 % of the nominal rated voltage; at ZS/ZL of 30, it is less than 0.5%. When the signals are this small, any errors in the voltage or current can be substantial relative to the theoretical values.

Figures 7 and 8 show actual CVT transients for High C and Extra Hi h C devices for a zero voltage fault. Note that the magnitude of the transient is approaching .15 to .2 per unit voltage. Similar transients will be obtained for faults at the end of a transmission line in those cases where the source to line impedance ratio is large (approximately greater than 10 . Consequently, the error voltage from t e CVT can be much larger than both the true 60 H z voltage and IZ-V operate signals.

Pilot Zone Reach

Because most directional comparison schemes include step distance backup protection, the ohmic reach of the pilot tripping elements are often based on the desired Zone 2 distance backup coverage. A typical value for the reach would be 125 percent of the impedance of the protected line. On short line applications, this may result in a pilot zone reach that is not much more than the Zone 1 reach in actual ohms. As a result, the pilot zone operating signal (IZ-V) for an end line fault will be low in magnitude. If the relay design is such that the operating time is a function of the magnitude of the operating signal, the speed of the pilot zone may be longer than desired. It is also possible that the current sensitivity will be higher than desired due to a low basic ohmic tap as discussed previously. If, on the other hand, the pilot zone is not set based on step distance considerations, it may be possible to improve the overall performance of the relay system by increasing the reach of the pilot,zone elements. Increasing the reach will increase the magnitude of the operating signal which in turn will decrease the operating time of the pilot tripping elements. The increased reach may also improve the current sensitivity of the relay by allowing a larger basic ohmic tap to be used.

If the pilot zone is not used for Zone 2 distance backup, its ohmic reach may be set many times the impedance of the protected line without having any adverse effect on the protection scheme. The design of some relay system may include a third zone of forward looking distance units so that a shorter reach may be used for Zone 2 step distance backup, while stil allowing a longer reach to be used on the pilot zone. However, even if the distance scheme is limited to two forward zones, a longer reach setting on the pilot zone should be considered. While the reach of the pilot zone may be several times the impedance of the line, when the length of the lines leaving the remote bus and the effects of current infeed at the remote bus are considered, the pilot zone may not overreach the protected line by as large a factor as the setting would indicate.

TLS/TYS Solution to CVT Transients

The General Electric Company protective relaying philosophy is to enhance the security of the protective relay system wit out impairing the reliability of the power system. As art of this philosophy, the protective relays are designed to provide high speed operation w here system stability may be a problem, and slower speed res onse for less severe faults where the danger of over reach increases. The typical solutions to C VT related relay problems is to add long time delays or to add filtering. However, filtering invariably tends to add delay to the o erating time of the measuring function for internal faults. Therefore, greater filtering resu lts in greater security but slower operating times. Thus, an optimal design must provide enough filtering to provide security against false tripping and at the same permit high speed tripping for severe internal faults.

The polarizing voltage signal used in the TLS/TYS relay systems is comprised of positive sequence voltage with memory. The use of positive sequence voltage provides a very stable polarizing signal which, in conjunction with the memory circuit, overrides the effects of the CVT transients on the polarizing signal of the mho distance units. In the operating or IZ-V circuit, the TLS and TYS relay systems use a combination of high and low bandpass filters and zero suppression (level detector) circuits to remove the CVT transients with minimal effect on the high speed performance required for severe faults. As the magnitude of the operating signal is reduced, the filtering becomes more effective and the speed of the unit is reduced. The net result is to produce a relay operating time vs distance to the fault time curve that increases as the IZ-V signal is reduced to the magmtude that CVT transients can cause a problem. Figure 9 shows the typical operating time of the TLS/TYS measuring units based on the magnitude of the IZ-V signal during the fault.

A block diagram of the operating signal processing is shown in Figure 10. The net operating signal is the sum of three processmg circuits:

1. The output from a high set zero suppression circuit.
2. The output from a bandpass filter with a Q of 2.
3. The output of a lower set zero suppression circuit.

The main operate signal is the output of the "A" filter which has a Q of 2. This filter removes non 60HZ components (such as CVT transients) from the IZ-V, but the bandpass filter introduces a time delay in the res onse of the output. The out ut from the "A" filter allows the unit to operate, with some time delay on low level IZ-V signals which typically occur for faults near the end of the relay reach. The high set zero suppression circuit is used to provide high speed operation for severe faults where the magnitude o the IZ-V signal is large. Since the level of the high set zero suppression circuit is 1.5 er unit voltage, the circuit is not affected by CVT transients. The third component of the net IZ-V operating signal is also used to provide high seed operation for severe faults. This circuit provides a transient response to the fault based on the interaction of the two bandpass filters ("A' and "B") which have different Q's. The low set zero suppression circuit level is based on the maximum 2VT transient.

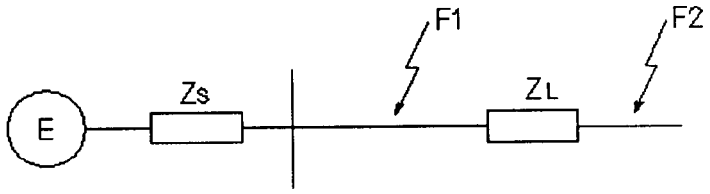
Summary

The application problems associated with protection of short lines are often a function of the ratio of the source impedance to the line impedance rather than simply the length of the line. Problems may arise with current only or with distance /directional schemes. The roblems with distance relays are compounded when CVT's are used, but with the proper knowledge of both the power system and of the relay design a successful distance or combination distance and directional overcurrent scheme can be implemented.

References

1. GER3199, "Application Guide for the Use of Distance Relays", a GE publication.

2. Korejwo, E., Synal, B., & Trojal, J, "Short H.V. Transmission Line Protection Problems", a paper presented at the IEE Second International Conference on Developments in Power System Protection, 1980.



E=67 V RMS

FIGURE 1

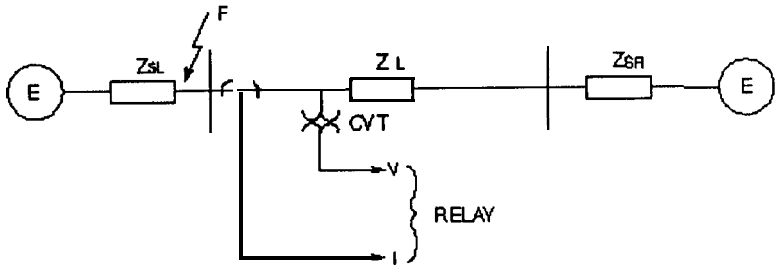


FIGURE 2

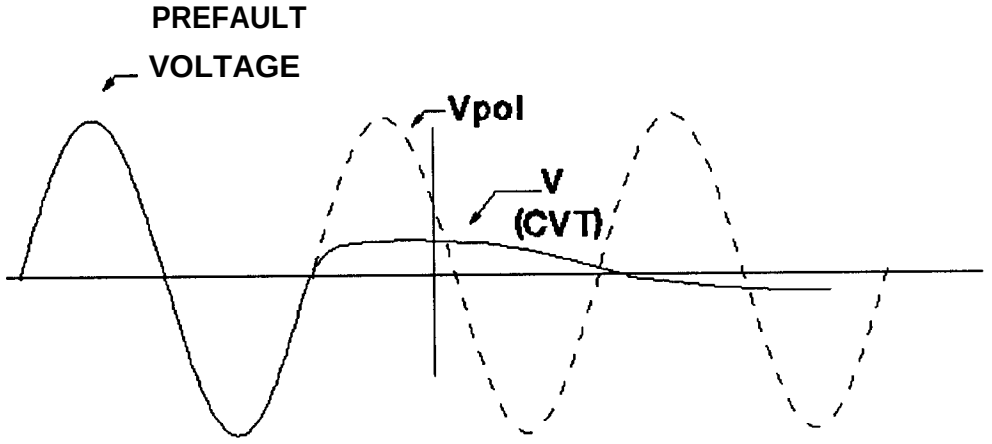
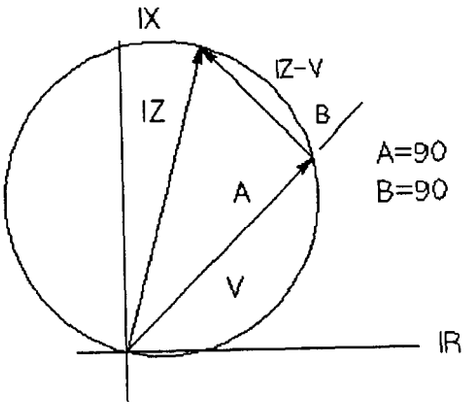
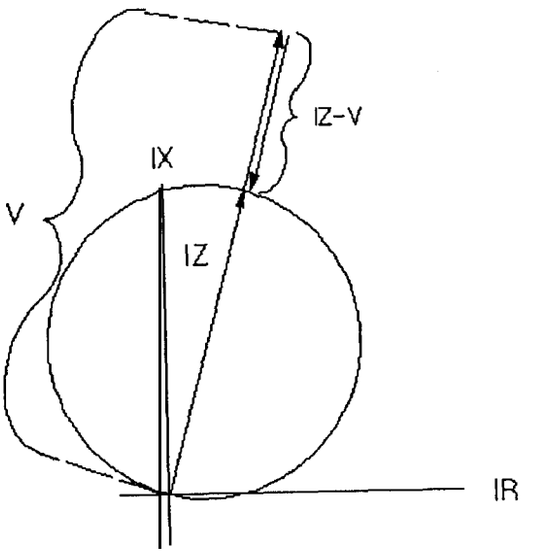


FIGURE 3

TYPICAL CVT TRANSIENT FOR A ZERO VOLTAGE FAULT



BALANCE POINT



EXTERNAL FAULT
AT LINE ANGLE

FIGURE 4

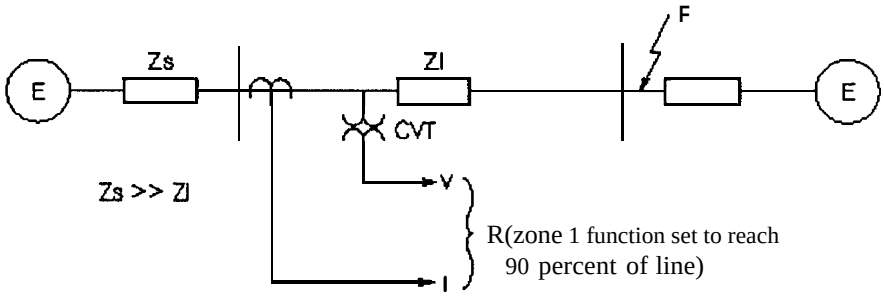


FIGURE 5

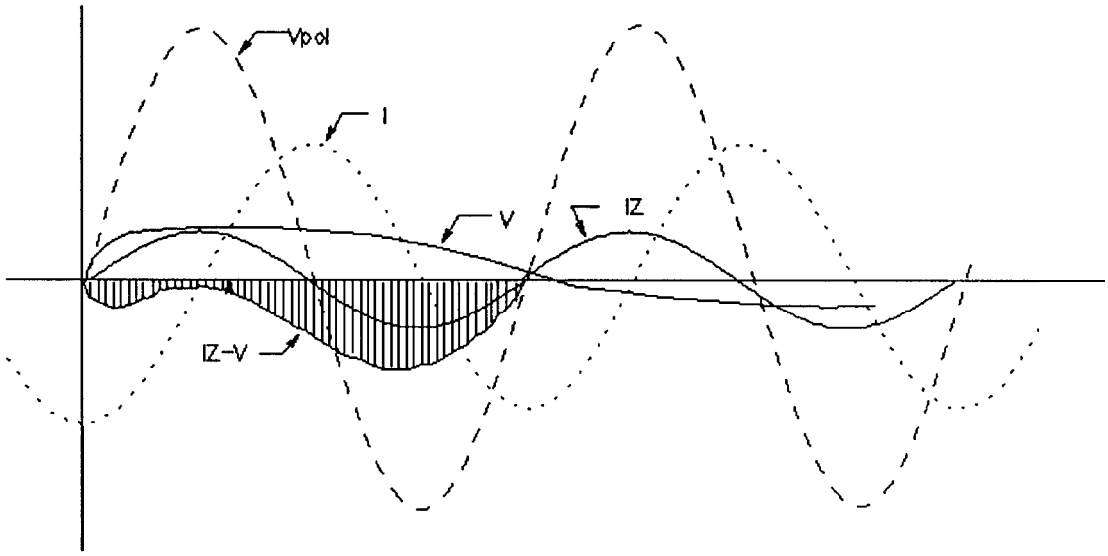
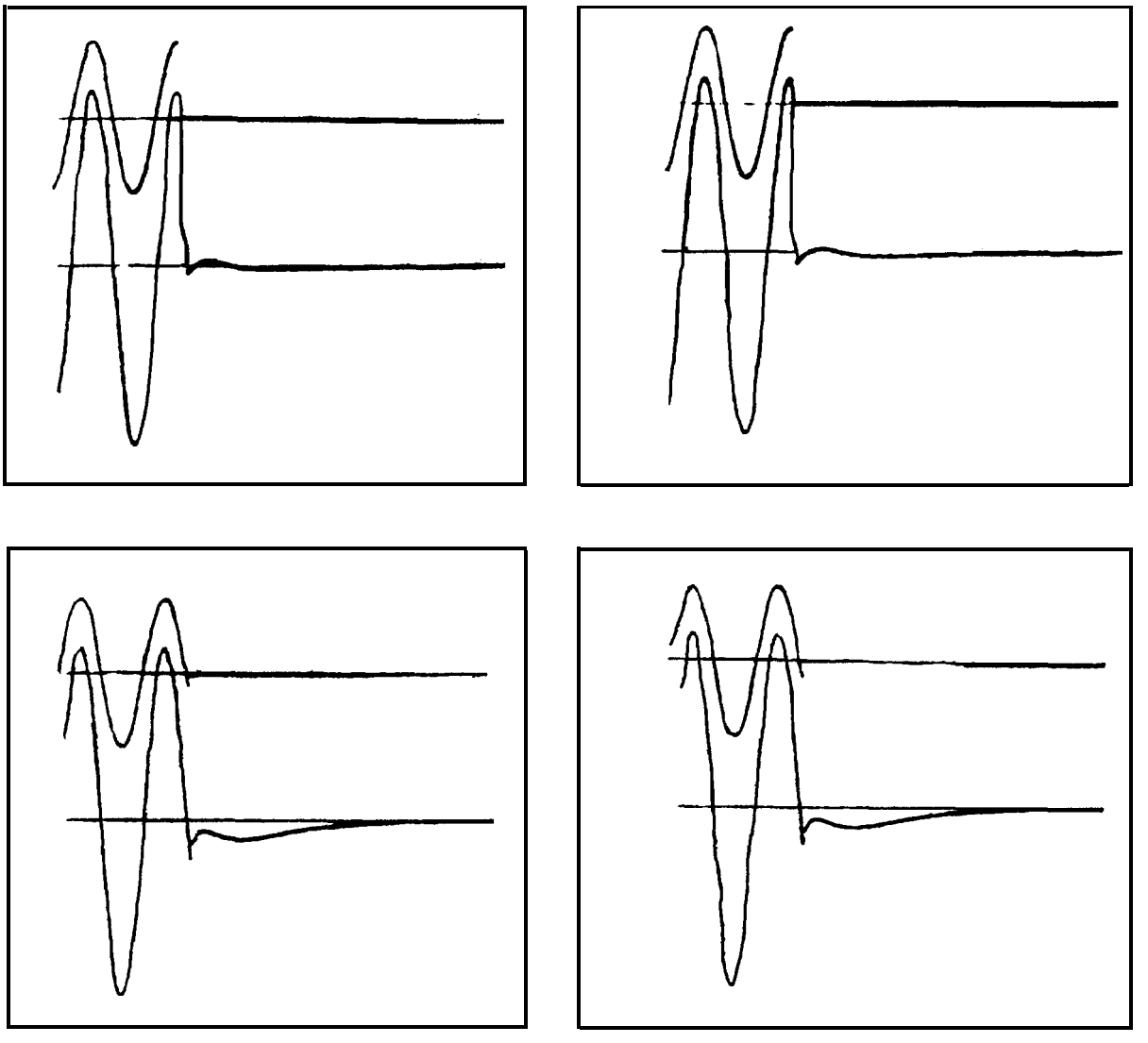


FIGURE 6

Response of First Zone Distance Function for End of Line Fault With CVT Transient

TRANSIENT RESPONSE TEST
4CD31DllS1*6*

INTERMEDIATE VOLTAGE EQUIVALENT CIRCUIT TEST



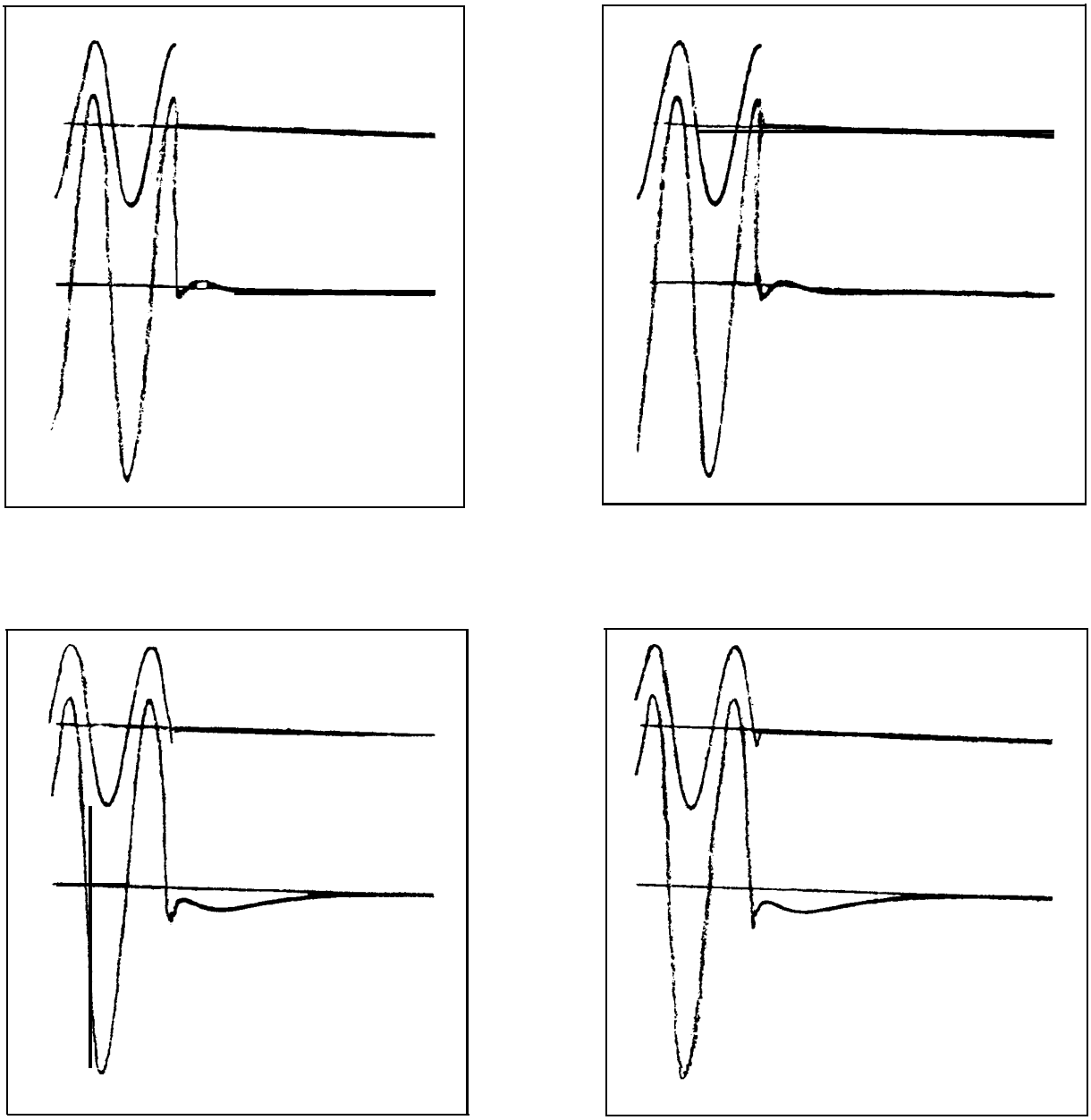
HIGH C CVT

UPPER TRACE: INPUT VOLTAGE
LOWER TRACE: SECONDARY VOLTAGE

Figure 7

TRANSIENT RESPONSE TEST
4CD51A34S*6*

INTERMEDIATE VOLTAGE EQUIVALENT CIRCUIT TEST



EXTRA HIGH C CVT
UPPER TRACE: INPUT VOLTAGE
LOWER TRACE: SECONDARY VOLTAGE

Figure 8

OPERATING TIME vs OPERATING SIGNAL (IZ – V)

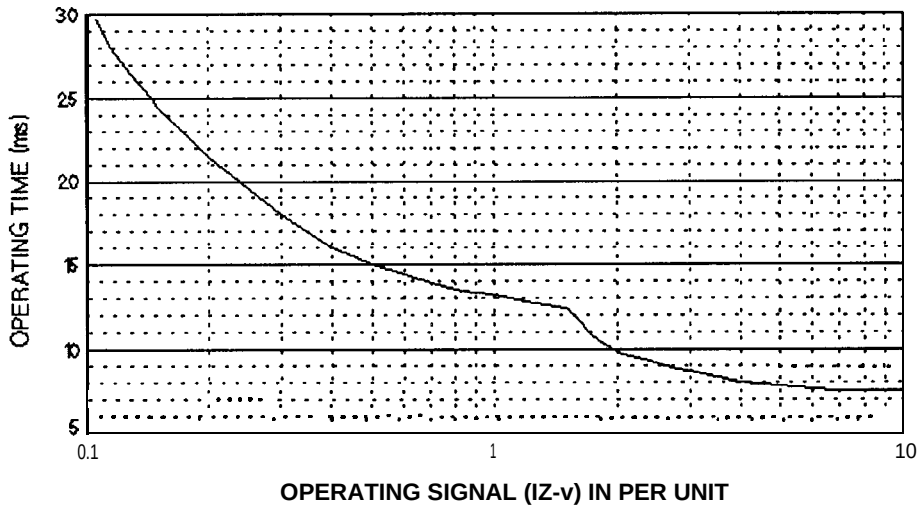


FIGURE 9

TYPICAL OPERATE CIRCUIT FOR RELAYS

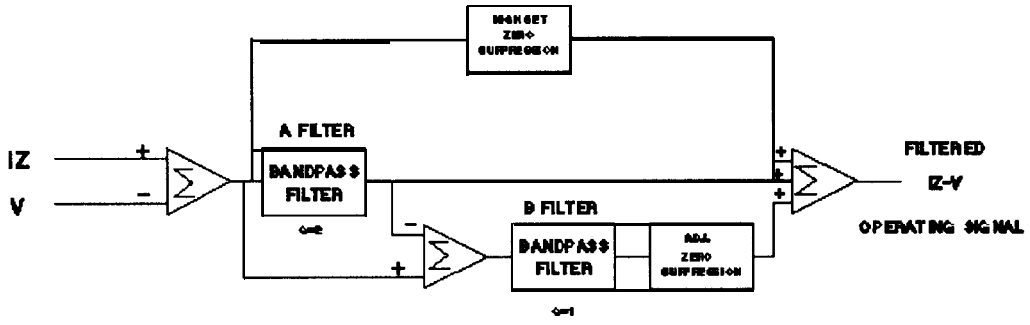


FIGURE 10